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WIND-TUNNEL INVESTIGATION TO DETERMINE THE CRITICAL ADVANCE RATIO OF THE 8/31-SCALE MCDONNELL MODEL 82 CONVERTIPLANE ROTOR

HANS K. DOETSCH
LEON MARK

AIRCRAFT LABORATORY

APRIL 1953

Statement A
Approved for Public Release

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WADC TECHNICAL REPORT 53-125 *SECURITY INFORMATION*

WIND-TUNNEL INVESTIGATION TO DETERMINE THE CRITICAL ADVANCE RATIO OF THE 8/31-SCALE MCDONNELL MODEL 82 CONVERTIPLANE ROTOR

Hans K. Doetsch
Leon Mark

Aircraft Laboratory

April 1953

RDO No. 446-47

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

[redacted]

53WC-43926-1

FOREWORD

This report was prepared by the Aircraft Laboratory, Directorate of Laboratories, Wright Air Development Center. The test was conducted in the Massie Memorial Wind Tunnel from February to May 1952. The test was initiated at the request of the Rotary Wing Branch of the Weapons Systems Division under Research and Development Project MX-1604 and Research and Development Order Number 446-47, (UNCL) "Aircraft, Convertiplane Type".

Mr. Kermit Riegel assisted in preparing and conducting the tests. The project engineers for the design of the model support system and other mechanical work were Messrs. Keith Cossairt and Karl Thormaehlen.

ABSTRACT

This report presents test results on the 8/31-scale McDonnell Model 82 Convertiplane in the Massie Memorial Wind Tunnel, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. The purpose of these tests was to determine the high-speed potential of the McDonnell rotor at a zero rotor angle of attack and in an approximately zero rotor lift condition.

The main results are as follows: The critical advance ratio, as defined by the development of unstable blade flapping of the model rotor, decreases from approximately 1.6 at 400 rpm to approximately 1.3 at 800 rpm. The Wright Field result at 400 rpm agrees with previous tests conducted by McDonnell in the University of Washington Aeronautical Laboratory Wind Tunnel with the same rotor and at the same rotor speed.

The considerable effect of rotor speed on the critical advance ratio was unexpected and no definite explanation can be given for it either from these tests or from the available theoretical treatments of the rotor blade motion. The theoretical investigations on rigid rotor blades indicate stable blade motion up to much higher advance ratios than measured during these tests. However, these theoretical investigations were made under simplifying assumptions which do not represent the true conditions on the rotor blades. Some of the discrepancies between these assumptions and the true blade conditions are discussed in this report. The discussion of the test results and their comparison with the results of References 3 and 4 shows that the knowledge about the nature of the observed blade instability is still insufficient and that more experimental and theoretical work is required to clarify the problem.

The security classification of the title of this report is UNCLASSIFIED.

PUBLICATION REVIEW

This report has been reviewed and is approved.

H. J. Lippman
for R. G. RUEGG, Colonel, USAF
Chief, Aircraft Laboratory
Directorate of Laboratories

TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

[redacted]

LIST OF ILLUSTRATIONS (Continued)

COEFFICIENTS, SYMBOLS, AND FORMULAE

I	mass moment of inertia of rotor blade about flap hinge, slug-ft^2
L'	rotor reference lift $(0.006\rho\pi R^2 V_t^2)$, Reference 7, lbs
M_H	blade horizontal bending moment (measured at 33% span), ft-lbs
$\overline{M}_H$	blade horizontal bending moment coefficient, $M_H/L'R$
M_V	blade vertical bending moment (measured at 33% span), ft-lbs
$\overline{M}_V$	blade vertical bending moment coefficient, $M_V/L'R$
R	rotor radius, ft
V	tunnel velocity, ft/sec
V_t	rotor tip speed, ft/sec
a	theoretical slope $dC_L/d\alpha$ for the blade section
b	number of blades
c	rotor blade chord, ft
n	rotor rotational speed, rpm
r	radial location on blade, ft
α_F	angle of attack with respect to fuselage reference line, degrees
α_R	rotor angle of attack (angle between the rotor shaft and a perpendicular to the flow direction), degrees
β_0	blade flapping angle, up positive, degrees (See Figure 5)
γ	blade inertia coefficient $\left(\frac{ac\rho R^4}{I}\right)$
μ	rotor blade tip advance ratio, V/V_t
μ_{crit}	critical advance ratio
ρ	air density, slugs/cu ft
ψ	blade azimuth position (aft position 0°), degrees

COEFFICIENTS, SYMBOLS, AND FORMULAE (Continued)

α airfoil angle of attack measured from zero lift position, degrees

C_L lift coefficient

C_{m_o} pitching moment coefficient about zero chord point

INTRODUCTION

The McDonnell Model 82 is a special approach to the convertiplane problem of combining vertical take-off with forward flight speeds higher than that of normal helicopters. The maximum design speed of the McDonnell Model 82 is 184 mph. At this speed the advance ratio (forward speed over rotor tip speed) is 0.94 which exceeds normal helicopter advance ratios by a factor of more than 3.

The purpose of the tests conducted in the Massie Memorial Wind Tunnel was to investigate the aerodynamic characteristics of the Model 82 in the conversion and high-speed range and to determine the speed potential of the design principle, that is, the upper speed or advance ratio limit of the rotor.

This report presents the results of the investigation of the blade flapping stability limit or critical advance ratio of the rotor. The results dealing with the aerodynamic characteristics in the range of conversion and high-speed flight will be presented in a Technical Note.

SECTION I

TEST EQUIPMENT AND PROCEDURE

A. Model

The model used in this test was an 8/31-scale McDonnell Model 82 convertiplane. A general arrangement drawing of the model may be found in Figure 1 and a photograph in Figure 2. Table 1 contains a list of the geometrical characteristics of the model. The model had a pylon-supported three-bladed 8-foot-diameter rotor. The rotor was powered by a hydraulic motor housed in the fuselage and pylon. The hub of the rotor, which is of the free-floating type in the helicopter flight range, was locked during the present phase of high-speed testing. There was no cylic pitch control during these tests.

The blades were constructed of laminated balsa with a hollow steel spar along the 24% chord line. The root sections of the blades consisted of a spar socket and two sets of steel tension straps to absorb the centrifugal force of the blades (Figure 3). These parts of the blades were covered with symmetrical streamlined cuffs fabricated from sheet aluminum. The blade inertia coefficient was approximately 4.6 (see list of coefficients, symbols, and formulae). The blades had zero twist and were balanced about the 24% chord line by a length of drill rod in the leading edge. The blade root and blade tip configurations are described in Table 2.

The rotor blades had an oblique (δ_3) flapping hinge with a pitch-flap coupling of 2.25 (Figure 5). From previous McDonnell tests, this pitch-flap coupling ratio was found to be close to the optimum ratio for compromising between reasonable one-per-revolution stable flapping amplitudes and a reasonably high stability limit of the one-half-per revolution mode (Reference 1).

B. Test Apparatus

The Massie Memorial Wind Tunnel, Wright Air Development Center, is a closed single-return type wind tunnel with a test section 20-feet in both diameter and length.

The model was mounted on the wind-tunnel six-component balance by two streamlined tandem struts (Figure 6). The model in the test position was inverted with respect to the normal flight attitude. This installation causes the weight moment of the blades to act in

the opposite direction, relative to the hinge, as compared with normal flight conditions. However, the weight moment is small as compared to the other terms and causes, mainly, a small change in the coning angle of the blade. The agreement between tests made by McDonnell at the University of Washington Aeronautical Laboratory with the model in a normal flight attitude (Reference 1) and the results presented here for 400 rpm proves that the effect of the weight moment on the blade flapping instability is negligible.

The rotor blades were equipped with strain gages mounted at the 1/3-span location. These gages indicated the horizontal and vertical bending moments M_H and M_V in the blades. A micro switch and a cam were installed on the rotor drive mechanism to determine rotor blade position and rotor speed.

One rotor blade had a thin cantilever beam, equipped with strain gages to record the flapping motion of the blade. The blade flapping restraint caused by the beam was negligible.

C. Test Procedure

For all tests described in this report the rotor was held at zero angle of attack. The pitch setting of the rotor blades was adjusted so that the rotor produced no lift while rotating at zero tunnel speed. Preliminary vibration studies of the rotor were conducted in which M_H and M_V records were taken through the rotor speed range at a constant advance ratio of 0.9. The results of these runs indicated that the rotor speed range between 600 and 850 rpm was free from any resonant peaks for either M_H or M_V. However, M_H appeared to be tending toward a resonant peak below 600 rpm. This is in agreement with the University of Washington tests of Reference 7 where a resonant peak in the neighborhood of 500 rpm was observed. The lowest rotor speed (400 rpm) used in these tests proved to be free again from any critical resonance.

At the same time the vibratory condition of the complete model and support system, especially the wing and tail booms, was observed and found to be satisfactory in the tested range of the rotor speed.

The rotor was dynamically balanced by adding small weights to the tips of the blades. The blades were very carefully tracked while running the rotor at zero advance ratio and were checked at a relatively high but still stable advance ratio. The tracking of the blades was considered to be satisfactory if the tip paths of the blades coincided within 0.25 inch.

The blade instability limit, or the critical advance ratio, was

determined by observation of the rotor. Somewhat below the critical advance ratio an irregularity appeared in the normal path of the blades. The blades started to flick out of track occasionally and then diverge. Once the blades became fully unstable they flapped violently from stop to stop inducing very high stresses in the spars. To prevent damage to the blades, every effort was made to avoid this fully unstable condition. As soon as the observer, while increasing the advance ratio, noticed the irregular motion of the blades and a divergence of the tip paths of about 3 or 4 inches, the blades were stabilized by increasing the rotor speed and thus decreasing the advance ratio. The highest advance ratio obtained by this procedure was considered to be the instability limit or the critical advance ratio.

The accuracy of the critical advance ratios determined by this procedure may vary, depending upon the magnitude of the tunnel velocity increase when approaching the critical advance ratio and upon the amount of divergence of the tip paths taken as an indication of instability. It is felt that the accuracy of the critical advance ratio is of the order of 0.05 to 0.1. This must be considered when comparing the effect of configuration changes.

SECTION II

RESULTS AND DISCUSSION

A. Data Evaluation

The dimensionless vertical and horizontal bending moments $\bar{M}_V$ and $\bar{M}_H$ were determined by reading the average maximum peak-to-peak amplitudes of M_V and M_H from the oscillograph traces. Half of these peak-to-peak values were considered the maximum alternating bending moments.

The tunnel speed was corrected for model and wake blockage by the methods presented in Reference 6.

B. Results

The rotor high-speed limit investigation in the Massie Memorial Wind Tunnel shows agreement with test results obtained by McDonnell in the University of Washington Wind Tunnel (Reference 2). However, these tests with the same rotor diameter of 8-feet were limited to a rotor speed of about 400 rpm because of the lower maximum test speed attainable in the University of Washington Tunnel. For the Wright

Field test the rotor speed had been set at 800 rpm in order to simulate the full-scale Mach number and to increase the Reynolds number above that of the University of Washington tests.

1. Effect of Rotor Speed on the Critical Advance Ratio

In order to correlate the previous McDonnell results with the present test results the critical advance ratio was investigated for rotor speeds between 400 and 800 rpm (Figure 7). The results of the tests at 400 rpm showed agreement with the University of Washington results. However, with increasing rotor speed the critical advance ratio dropped from 1.56 at 400 rpm to 1.2 at 800 rpm for the basic rotor (Configuration (a)).

Since this rather large and unexpected effect of rotor speed on the critical advance ratio may possibly be important in the application of the test results to the full-scale rotor, configurations (c) to (f) in Table 2 were improvised during these tests in order to find an explanation for this behavior. However, all configurations described in Table 2 showed essentially the same characteristics.

2. Effect of Configuration Changes on the Critical Advance Ratio

The basic rotor configuration (a) had faired tip burners installed (Figure 4). When the faired tip burners were replaced by square tips, configuration (b), the critical advance ratio was found to be somewhat lower in the high rotor speed range. Small spanwise shifts in the blade center of gravity had no influence on the critical advance ratio as indicated by the results on configuration (c). Also, increasing the in-plane and vertical natural frequency of the blade by increasing the blade stiffness in configurations (d) and (e), Table 2, was found to be without effect. For configurations (e) and (f) the blade cuffs had to be removed. It should be mentioned that according to the McDonnell results of Reference 2, the removal of the cuffs increased the critical advance ratio by approximately 0.1. This indicates that the somewhat higher advance ratios found with configurations (e) and (f) were not necessarily caused by the changes on the outer blades, but more probably by the removal of the cuffs.

As stated in Section IC, it cannot be claimed that the critical advance ratio had better accuracy than 0.05 to 0.1. If this is taken into consideration, it follows from Figure 7:

a. All changes made on the basic blade configuration had no definite effect on the critical advance ratio.

b. All configurations showed the same rotor speed effect —— a decrease in the critical advance ratio from about 1.6 at 400 rpm to about 1.3 at 800 rpm.

3. Blade Bending Moments

During the investigation of the rotor instability the blade bending moments and blade flapping angles were recorded by an oscillograph. Figures 8 to 11 show the alternating horizontal and vertical bending moments ($\overline{M}_H$ and $\overline{M}_V$) plotted versus the rotor advance ratio. When approaching the critical advance ratio, the horizontal bending moment in general indicates a very sharp stress increase. Some of the $\overline{M}_V$ curves show similar characteristics but some exhibit constant slope throughout the test range.

4. Blade Flapping Angle

Figures 12 to 15 present sample records of the blade flapping angle β_o versus the blade azimuth position ψ . In the original test program for the Wright Field tests it was not intended to conduct a detailed investigation of the blade flapping instability. The program called only for the determination of the critical advance ratio which was expected to agree with previous McDonnell test results. Therefore, when the problems connected with the unexpected influence of rotor speed on the critical advance ratio appeared, only a few improvised configuration changes and tests could be conducted.

Due to the excessive blade flapping in the unstable region and the necessity of avoiding rotor damage, very few records were accomplished for conditions at or near the critical advance ratio.

Figure 12 shows the flapping angle for configuration (a) at 400 rpm versus the azimuth angle ψ for the advance ratios of 0.9 to 1.45. From Figure 7 it can be seen that the critical advance ratio at 400 rpm was 1.56. The complete range from 0.9 to 1.45 is therefore stable. The flapping motion of the blade at $\mu = 0.9$ consists mainly of a one-per-revolution mode. With increasing advance ratio, up to 1.45, the predominant term is still the one-per-revolution; however, higher modes appear more and more pronounced at the higher advance ratios.

Figure 13 presents the flapping angle versus the azimuth angle ψ for configuration (a) at 800 rpm between advance ratios of $\mu = 0.5$ and $\mu = 1.21$. Fortunately, in this case an oscillograph record was taken during the test condition which the observer considered to be the critical advance ratio. The lower advance ratios

exhibit the same characteristics as the results at 400 rpm (Figure 12). Between $\mu = 0.7$ and $\mu = 1.1$ the flapping motion changes gradually but maintains its character, and the maximum deflections increase very little. However, the step from $\mu = 1.1$ to $\mu = 1.21$ causes a complete change in the character of the flapping motion and an appreciable increase in the flapping amplitudes. This sudden increase of the amplitudes can be taken as an indication of approaching instability. The predominant mode in the diagram for $\mu = 1.21$ is no longer the one-per-revolution but a one-half-per-revolution blade flapping mode.

Another set of records for configuration (a) is presented in Figure 14. These records were obtained at a rotor speed of 600 rpm. The record for the advance ratio $\mu = 1.5$, which was taken as the critical advance ratio, shows two well pronounced cycles of the unstable one-half-per-revolution blade flapping mode; whereas, the other cycles recorded have definitely increased, but not excessive amplitudes when compared with the stable records of the lower advance ratios. This indicates that the record for $\mu = 1.5$ was taken at a rotor condition which was approaching the limit of instability.

The records presented in Figure 15 for configuration (b) at a rotor speed of 700 rpm are similar to those of Figure 13. The records for the advance ratios $\mu = 1.1$ and $\mu = 1.25$ indicate a stable blade flapping motion. However, the very small step from $\mu = 1.25$ to $\mu = 1.252$ causes a complete change in the character of the blade flapping motion and an appreciable increase in the flapping amplitudes. This is an indication of approaching blade instability as explained above.

During the instability tests an attempt was made to photograph the blade motion and the blade itself with a 500 frame-per-second camera. However, because of the relatively short time covered by one reel of film, pictures of the fully unstable motion were never obtained.

C. Discussion of Results

The test results described in Paragraph B indicated critical advance ratios between $\mu = 1.6$ and $\mu = 1.3$, dependent upon the rotor speed for all configurations tested. This order of magnitude for the critical advance ratio found by the tests does not agree with theoretical calculations of References 3 and 4. The most detailed theoretical investigation so far has been made by Horvay (Reference 3). He studied the stability of blade flapping for a rigid hinged blade with the hinge perpendicular to the blade axis. According to his calculations blade instability for all practical blade inertia coefficients will occur only above an advance ratio of 2. However, Horvay did not include in his equations the effect of blade stall

and reversed flow. Therefore, his calculations cannot be considered to be valid beyond an advance ratio of 0.5. But the calculations in Reference 3 show the basic fact that the natural frequency of the flapping motion in forward flight at advance ratios up to about $\mu = 1.2$ is one-half-per-revolution and that with increasing advance ratio the corresponding mode becomes less and less damped until a minimum damping is reached at $\mu = 0.85$. Above $\mu = 0.85$ the damping increases again. According to Reference 3 the one-half-per-revolution blade flapping mode is stable. This is not in agreement with the results of the Wright Field and the University of Washington tests which indicated that the one-half-per-revolution mode became unstable at the higher advance ratios (Figures 13 to 15).

Another theoretical investigation made by Hohenemser (Reference 4) took the blade stall and reversed flow into account using the actual airfoil normal force coefficient for the NACA 0015 airfoil section in the total range of 360° angle of attack.

The investigation in Reference 4 was made for a rigid blade with an inertia coefficient of 5, a pitch flap coupling of 2.25, and an advance ratio of 1.5. The result of the calculations indicated stability of the blade. This again is not in agreement with the Wright Air Development Center and the McDonnell test results which established a definitely unstable flapping motion in the range of $\mu = 1.2$ to $\mu = 1.6$. Besides this discrepancy between the values of the critical advance ratio obtained from these tests and the theoretical values from References 3 and 4, there is the additional test result which shows a pronounced effect of rotor speed on the critical advance ratio. The reason for this result could not be clarified during the tests and is not predicted in the results of References 3 and 4. The many possible reasons for the discrepancy between the theoretical and experimental values of the critical advance ratio and for the effect of rotor speed on the critical advance ratio are discussed briefly as follows:

1. Reynolds Number

With increasing rotor speed (between 400 and 800 rpm) the Reynolds number of the blade changes appreciably. From Figure 16 it is found that the tip Reynolds number for the advancing blade ($\psi = \frac{\pi}{2}$), at the critical advance ratio, changes from about 1.0×10^6 at 400 rpm to about 1.7×10^6 at 800 rpm. Naturally there are regions on the advancing blade ($\psi = 0$ to π) which work at much lower Reynolds numbers. For instance, at $\psi = 0$, $\frac{r}{R} = 0.2$, and at 400 rpm the Reynolds number 77,000; for a speed of 800 rpm the

Reynolds number is 154,000. In the range of low lift coefficients no appreciable effect of the advancing blade Reynolds number can be expected on the blade profile characteristics which could explain the effect of rotor speed.

The situation on the retreating blade is not as clear. The local Reynolds numbers of the blade cover a range between zero and a maximum. Besides, there is an extended region on the blade and the azimuth angle ψ where the flow is reversed with respect to the blade profile. It is clear that the Reynolds number range on the retreating blade contains critical regions where the aerodynamic coefficients of the profile may change appreciably. However, the significance of such possible effects may be minimized because of relatively small dynamic pressures. Without detailed investigations it is not possible to decide whether or not the Reynolds number effects on the retreating blade could influence the effect of the rotor speed on rotor blade instability.

2. Mach Number

The tip Mach number on the advancing blade was in the order of magnitude of 0.4 for 400 rpm and 0.7 for 800 rpm. These are below the critical Mach numbers which can be expected for the blade profile under the low-load conditions of the high-speed tests. There is, therefore, no reason to believe that the decrease in critical advance ratio with increasing rotor speed is caused by a Mach number effect.

3. Blade Stiffness

All theoretical calculations so far have been made with the blade regarded as infinitely stiff. However, in practical cases aeroelasticity could influence the blade motion. Therefore, configurations (d) and (e) which had increased in-plane and vertical bending stiffness were tested. It can be assumed that the torsional stiffness of the blades was not affected by the modification comprising configurations (d) and (e). No definite effect on the critical advance ratio could be noted in the relatively small range of bending stiffness variation used in these tests. However, it seems possible that torsional elasticity and parameters such as the locations of the elastic axis, the center of gravity, and the aerodynamic center — all important in the consideration of flutter — could have influenced all of the present test results. It is believed that more experimental work is required in order to clarify the possible influence of aeroelasticity on the critical advance ratio.

4. Velocity in the Direction of Blade Span

In the theoretical calculations the velocity components in the direction of the blade span have been neglected. Their exciting moments on the flapping blade in the forward positions ($\psi - \pi$) very probably can be assumed to be negligibly small.

5. Reversed Flow

The calculations made in Reference 4 took into account the influence of reversed flow by using the 360° lift polar for the symmetrical NACA 0015 airfoil section; whereas, the blade section of the McDonnell rotor is the unsymmetrical NACA 23015 airfoil section. No test results are available for this airfoil section over the 360° angle of attack range; therefore, it is not possible to show the effect of a flow reversal on this unsymmetrical airfoil section as compared to the symmetrical NACA 0015. But it may be of some interest to discuss qualitatively the effect of reversed flow on a cambered airfoil section with the aid of a test result on the Goettingen 420 (Reference 5) and to compare it with the effect on a symmetrical section.

In Figures 17a and 17b lift and moment coefficients are presented in the range of small angles of attack for normal and reversed flow conditions. Assume that the blade is at an angle of attack for zero lift, or near zero lift, in the normal flow condition at the moment when the flow reverses. In the reversed flow condition the blade lift coefficient will then change suddenly by an increment which is dependent upon the airfoil section. For the Goettingen 420 (Figure 17a) this change amounts to approximately $\Delta C_L = 0.50$. For a symmetrical blade ΔC_L would be zero. There is also one angle of attack on a cambered airfoil for which ΔC_L is zero. It is the intersection point for the lift curves in normal and reversed flow. For the Goettingen 420 this C_L value is 0.22. It is obvious that a symmetrical airfoil has effects similar to a cambered airfoil if the angle of attack is different from zero. From the standpoint of small flapping angles at high advance ratios, a zero or small lift on the blade is desirable; and from the standpoint of a stable flapping motion, any lift jump on the blade when the flow reverses is undesirable, especially because of the fact that the pitch-flap coupling tends to increase the excitation in this range.

There is another effect of reversed flow on the cambered blade which was not taken into account in Reference 4. For a symmetrical profile the moment coefficient is zero for zero lift coefficient in normal and reversed flow, and if the effect of the blunt trailing edge in reversed flow can be assumed to be negligible, the center of pressure and the aerodynamic center change from about 25% to about 75% chord location. This can be different for a cambered wing as

indicated in Figure 17b for the Goettingen 420 airfoil section. For this section C_m at $C_L = 0$ changes from -0.1 to +0.3 which is approximately twice what could be expected for a circular arc airfoil. The aerodynamic center is far behind the theoretical location (75%). Actually it is located at about 110% of the chord.

While the direct effect of the change in the aerodynamic moment characteristics of the profile on the pitch flap motion is very likely negligible for an infinitely rigid blade when compared with the effect of the lift change, this may not be the case with respect to the previously mentioned flutter parameters for an elastic blade.

As mentioned before, the lift and moment curves of Figure 17 cannot be considered as representative for the actual profile of the McDonnell blades. When presenting these curves it was only intended to show that a cambered profile can behave in a manner quite different from a symmetrical profile in reversed flow.

6. Unsteady Aerodynamic Forces

There is another possible reason for the discrepancy between theory and tests. It may be that the unsteady aerodynamic forces on the blade cannot be satisfactorily approximated by the quasi-steady forces as done so far in the theoretical treatments of References 3 and 4. Compared to the well-known aerodynamic forces in normal wing flutter considerations, the rotational nature of the blade motion and the periodic change of the velocity relative to the blade introduces new problems. Furthermore the effect of the centrifugal force and of the periodic change of the velocity on the boundary layer of the blade is unknown. Also this effect may cause the actual unsteady aerodynamic forces to differ from those in steady conditions, especially in regions of separation or transition.

From the above discussion of the test results, it follows that the knowledge about the actual nature of the blade instability as experienced in the present tests is still insufficient.

SECTION III

SUMMARY AND RECOMMENDATIONS

The most important results and conclusions obtained from these tests are as follows:

(1) All rotor configurations which were tested (See Table 2)

had the same critical advance ratio within the test accuracy of $\Delta\mu = 0.05$ to 0.10.

(2) All configurations showed the same effect of rotor speed on the critical advance ratio decreasing from about $\mu = 1.6$ at 400 rpm to about $\mu = 1.3$ at 800 rpm.

(3) Theory of infinitely stiff blades and test results do not agree. According to theory the blades should be stable in the range of advance ratios tested. No definite explanation can be given for the discrepancy between theory and test, especially for the effect of rotor speed on the blade instability.

(4) From the results of this test there is no reason to believe that the McDonnell Model 82 full-scale rotor could not fulfill its design performance of 184 mph or the maximum advance ratio of approximately $\mu = 0.94$. However, it is not possible to establish, from these tests, any definite speed potentiality for the full-scale McDonnell rotor in airplane flight; the principal reason is the fact that the exact nature of the observed blade instability is unknown. There is no doubt that further experimental and theoretical work is necessary to clarify the problem. The following points appear to be worthy of investigation:

(a) Determine whether aeroelasticity or flutter is involved in the unstable blade motion by testing blades with bending and torsional stiffness varied within large limits.

(b) Improve theoretical calculations by improving the assumptions on aerodynamic forces:

1. By using the actual 360° lift and pitching moment characteristics of the true blade profile. Because of the lack of this information, tests are recommended on the NACA 23015 and NACA 0015 profiles.

2. By studying the unsteady forces which, so far, have been approximated by quasi-steady forces in the theoretical investigations.

(c) Because of the complexity of the problem and the complexity of all theoretical investigations, direct measurements of blade section normal forces might be taken into consideration. This could be accomplished by pressure measurements on the rotating blade. (With present day testing techniques this appears possible, although such an investigation would be rather complicated.)

(d) With respect to the special question of the correct speed potentiality of the full-scale McDonnell Model 82 rotor, it is probably advisable to investigate the full-scale rotor in a large wind tunnel.

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[redacted]

TABLE 1

Wing		
Airfoil section	NACA	63_2A215
Incidence inner panel, degrees		8
Incidence outer panel, degrees		5
Geometric twist, degrees		3 linear
Area, square feet		6.63
Span, feet		6.71
Mean aerodynamic chord, feet		1.008
Root chord, feet		1.71
Aspect ratio		6.76
Dihedral, degrees		0
Taper ratio (outer panel)		0.66
Sweepback (25% chord line outer panel), degrees		11.5
Location of L. E. of root chord	FS	37.06
Location of 25% MAC	FS	44.03
Fuselage		
Nose, inches	FS–	0
Rotor centerline, inches	FS	37.03
Over-all length, feet		7.83
Center of gravity, inches	FS	37.03, WL 15.0
Tail (Horizontal)		
Airfoil section	NACA	0012
Area, square feet		1.40
Span, feet		2.11
Chord, feet		0.54
Aspect ratio		3.90
Incidence to fuselage, degrees, variable		±5
Taper ratio		1.0:1.0
Tail length (Rotor centerline to 1/4-chord of the tail), feet		4.32
Tail (Vertical		
Airfoil section	NACA	0012
Area (2 tails), square feet		1.39

TABLE 1 (Continued)

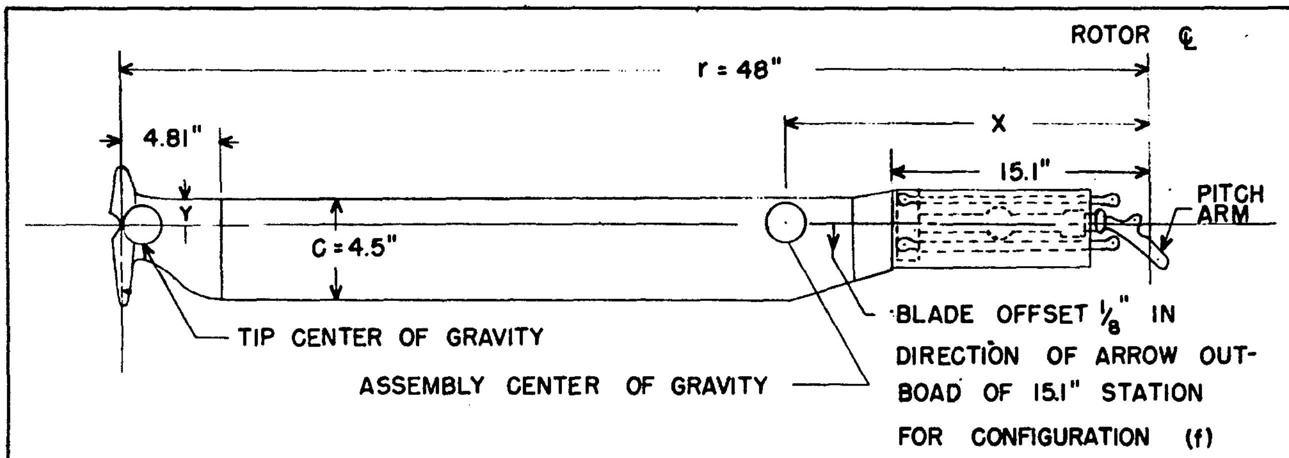
Rotor

Rotor diameter, feet	8.0
Area rotor disc, square feet	50.27
Solidity ratio, $\sigma = \frac{bc}{\pi R}$	0.09
Airfoil section	NACA 23015
Blade area, square feet	4.5
Blade chord, feet	0.375
Rotor pitch flap coupling ratio	2.25:1

[redacted]

TABLE 2

Rotor Blade Assembly Weight, Configuration (a), 3.35 Lbs Per Blade Assembly						
Configuration	Blade CG Location $\frac{x}{R}$	Tip Configuration & Weight of Tip Assembly	Chordwise CG Location y/c		Rotor Blade Configuration	Root Configuration
			Blade	Tip		
(a)	35.5%	Faired Tip Burners 0.14 lbs	24%	34%	Blade as Described in Section I,A.	Symmetrical Airfoil Section t/c = 28.4%
(b)	35.5%	Square Tips	24%	—	Same as Configuration (a)	Same as Configuration (a)
(c)	37.0%	Faired Tip Burners 0.22 lbs	24%	24%	Same as Configuration (a)	Same as Configuration (a)
(d)	36.8%	Faired Tip Burners 0.22 lbs	24%	24%	0.6 lb Insert added to Blade Spar. Increased In-Plane Natural Frequency at zero Rotor Speed from 930 to 1090 cpm.	Same as Configuration (a)
(e)		Faired Tip Burners 0.22 lbs	—	19%	Inserts in Leading and Trailing Edges of the Blades.	Unfaired (Cuffs Removed)
(f)	38.0%	Faired Tip Burners 0.22 lbs	24%	19%	Blade Offset 1/8-inch Rearward as Shown Below	Unfaired (Cuffs Removed)



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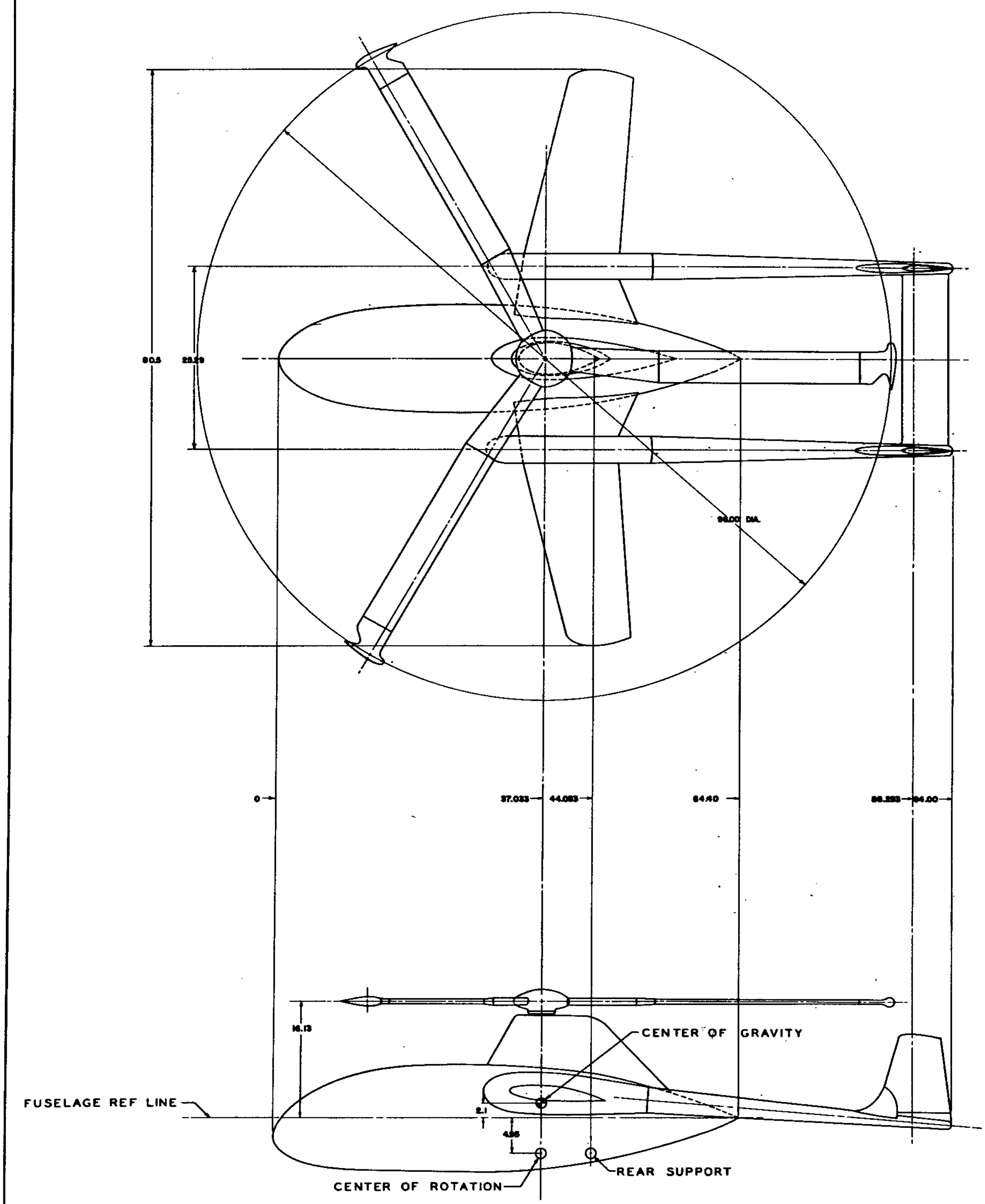

FIGURE I: GENERAL ARRANGEMENT OF 8/31 SCALE McDONNELL MODEL 82 CONVERTIPLANE

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

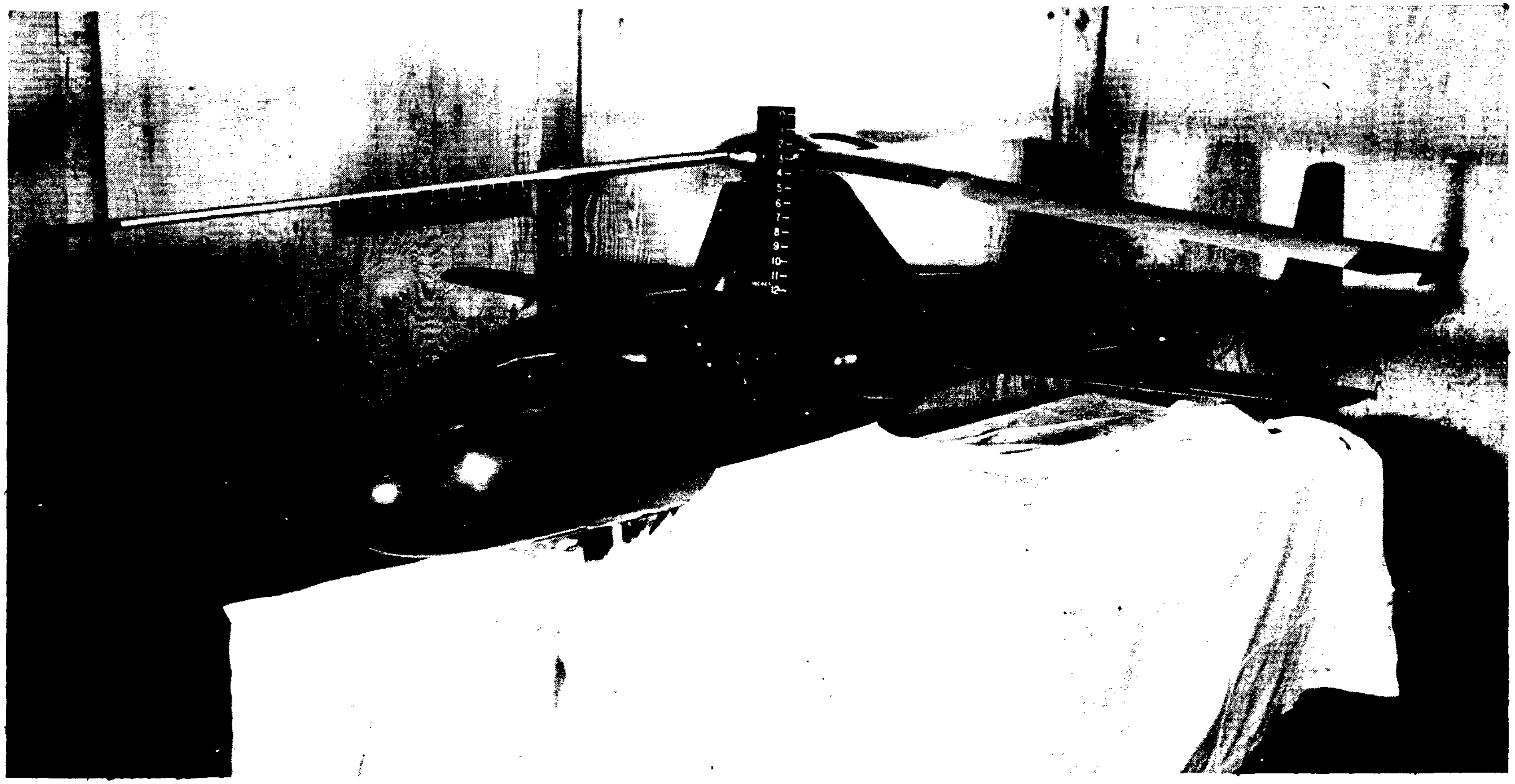

Figure 2: Complete Model, McDonnell 82 Convertiplane.

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

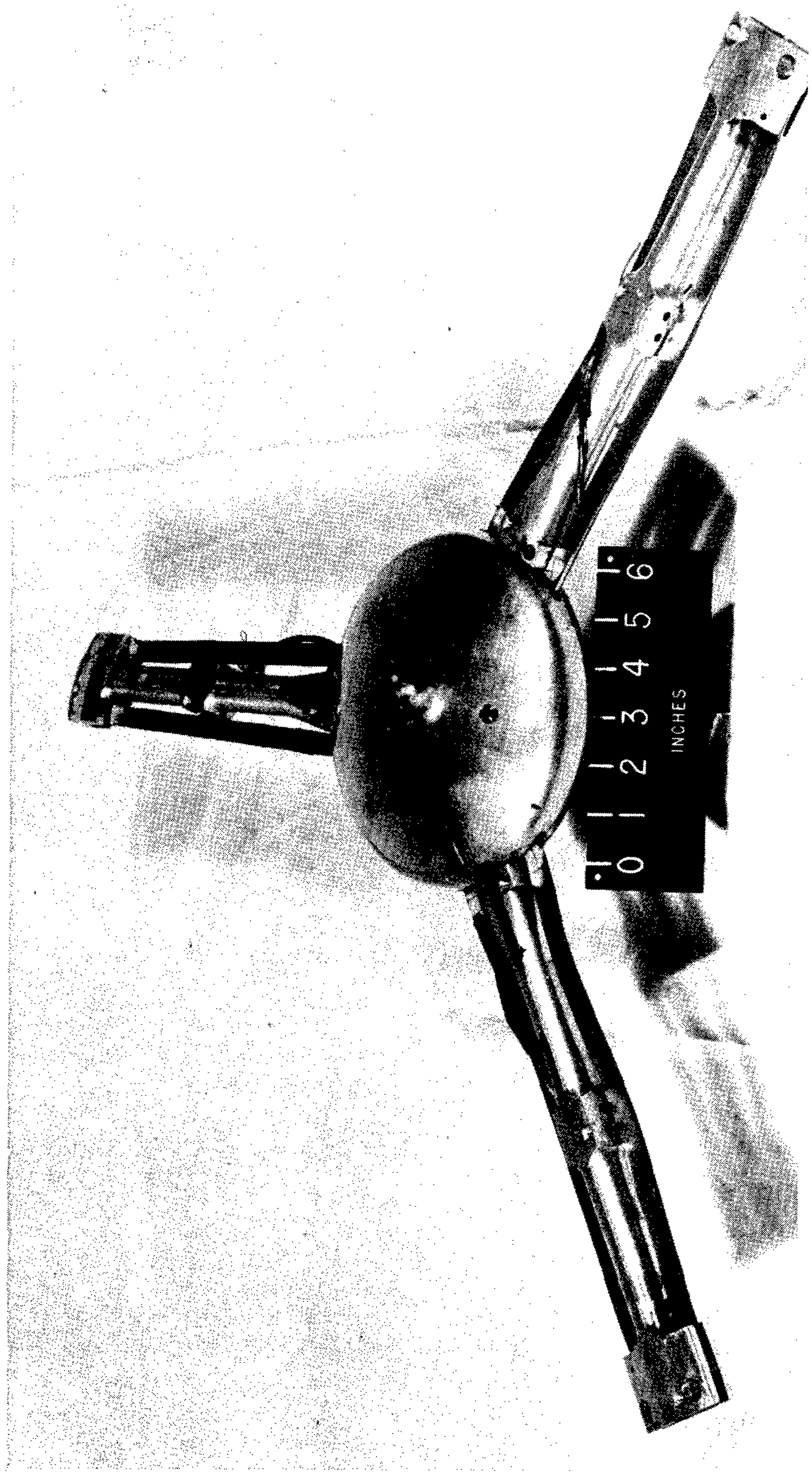

Figure 3: Rotor Hub and Blade Sockets, McDonnell Model 82 Convertiplane.

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

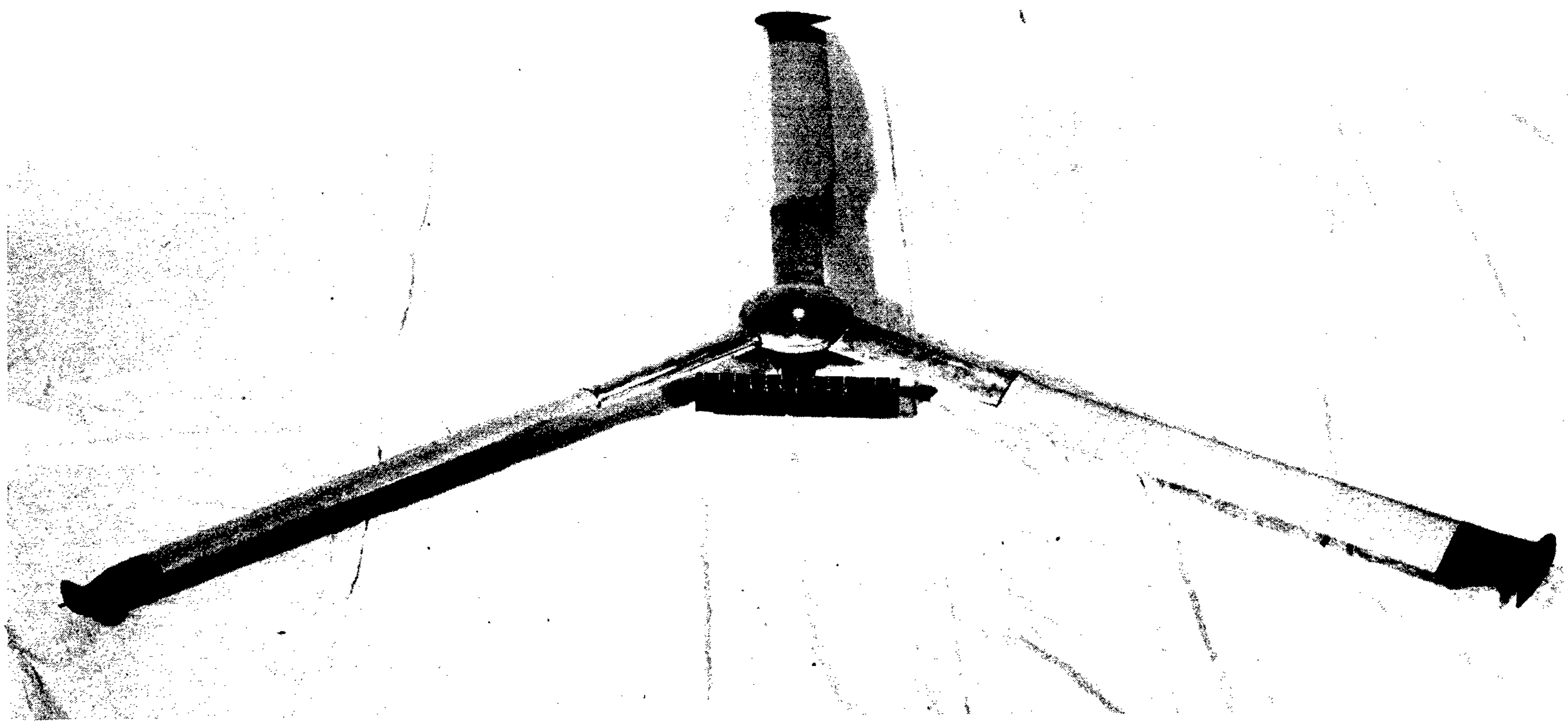

Figure 4: Complete Rotor, McDonnell Model 82 Convertiplane.

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

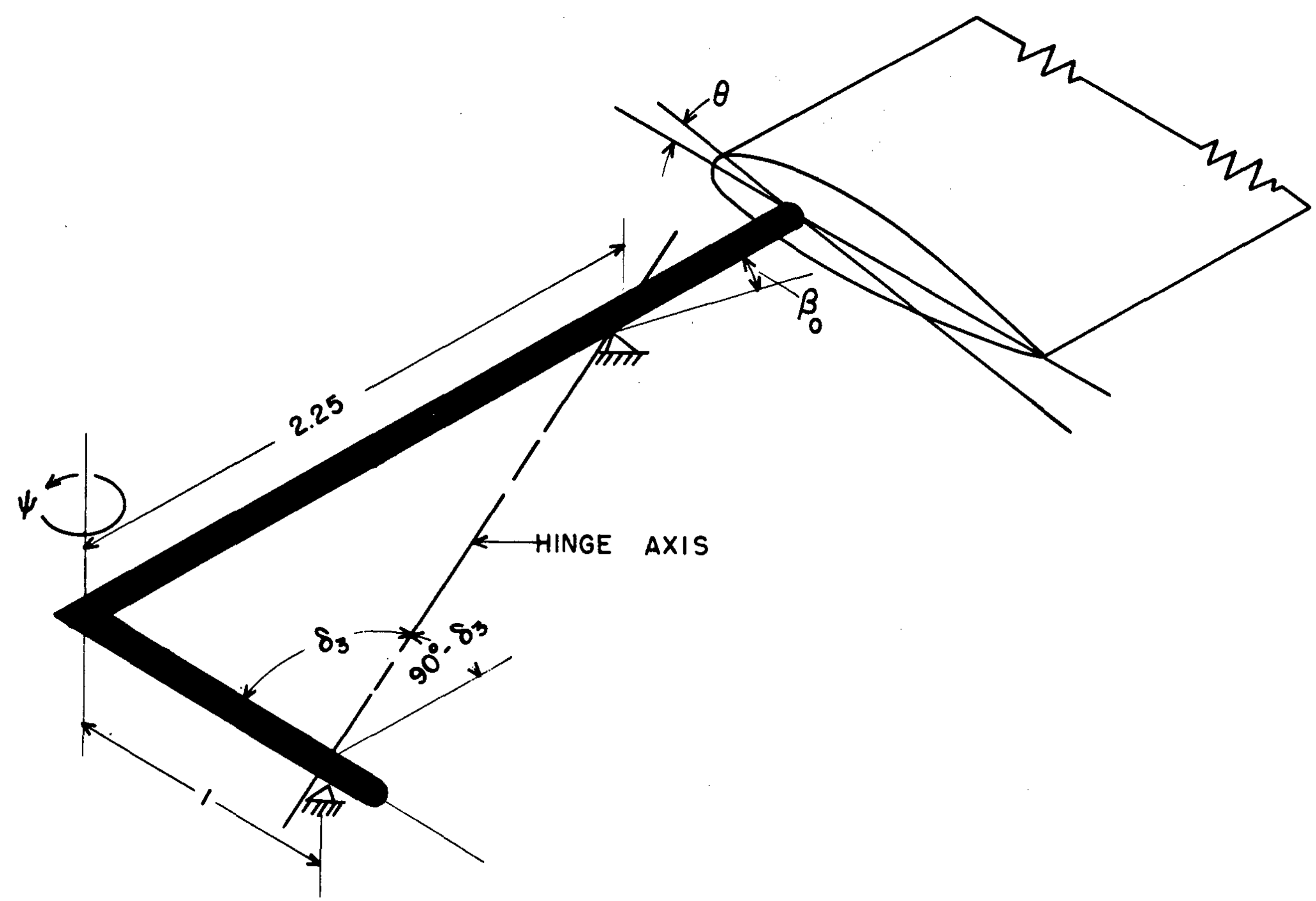

Figure 5: Schematic of the Pitch Flap Hinge McDonnell Model 82 Convertiplane.

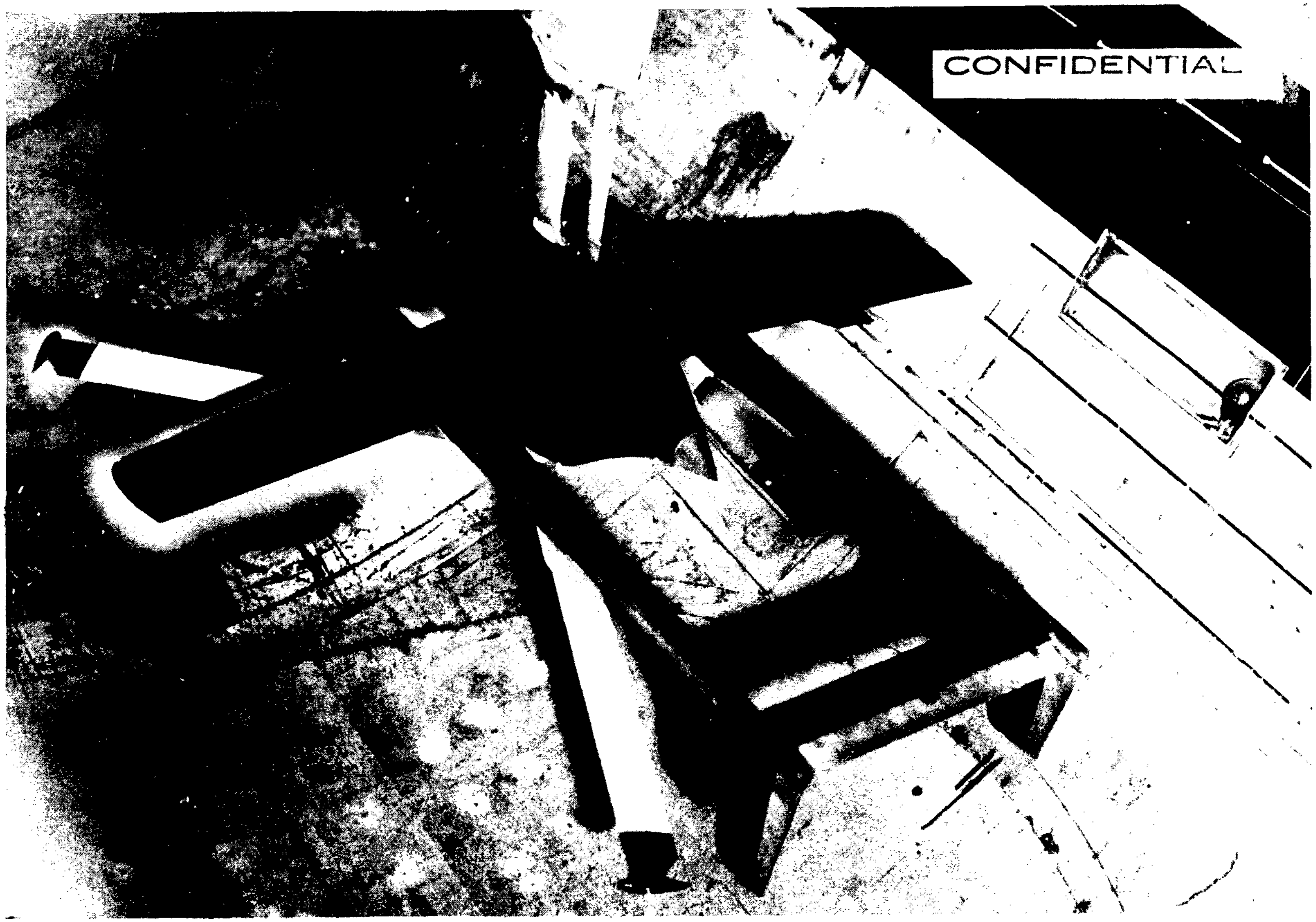

Figure 6: Complete Model, McDonnell 82 Convertiplane as Supported in the Massie Memorial Wind Tunnel.

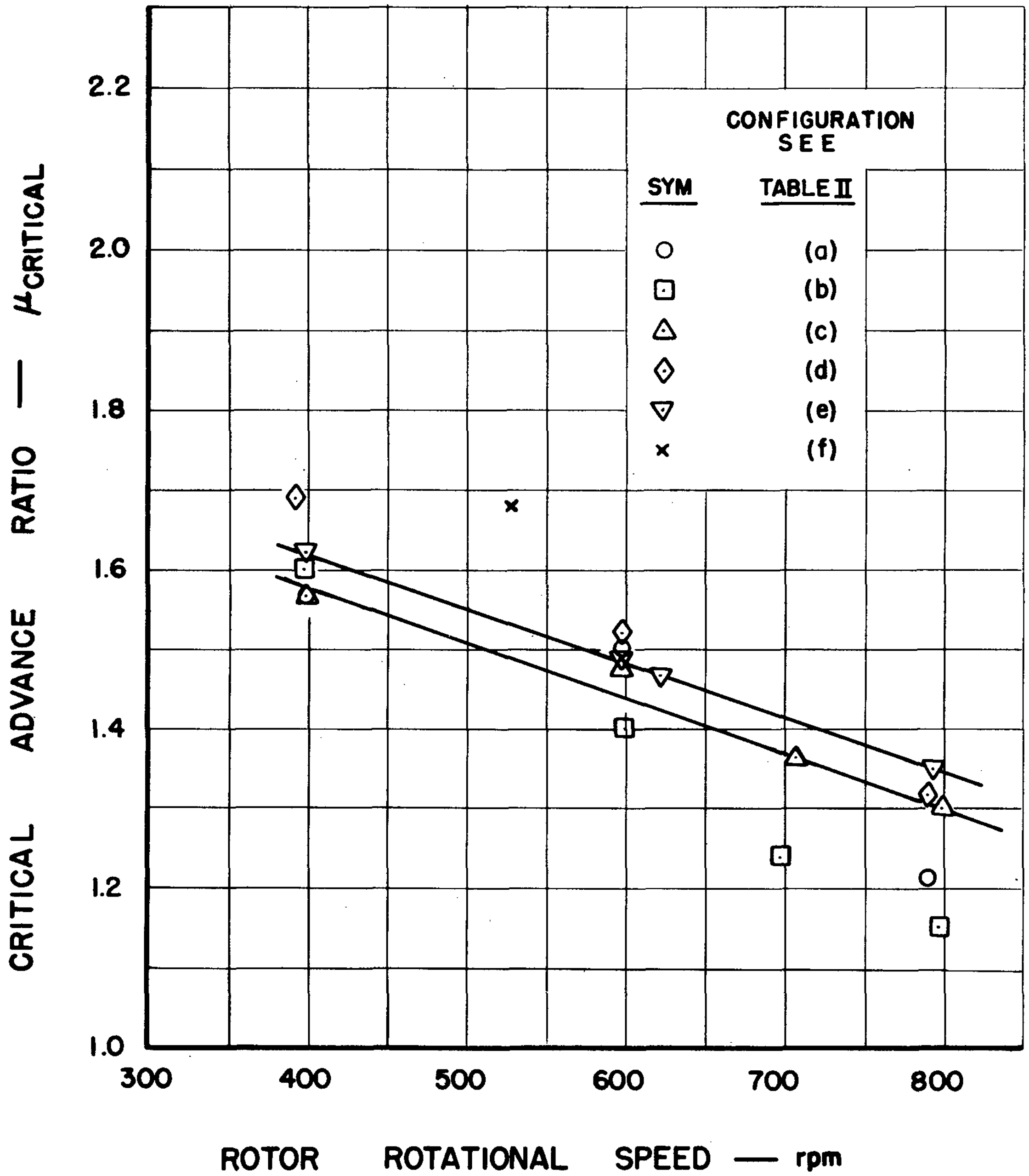

Figure 7: Variation of the Critical Rotor Advance Ratio With Rotor Rotational Speed for Various Rotor Configurations.

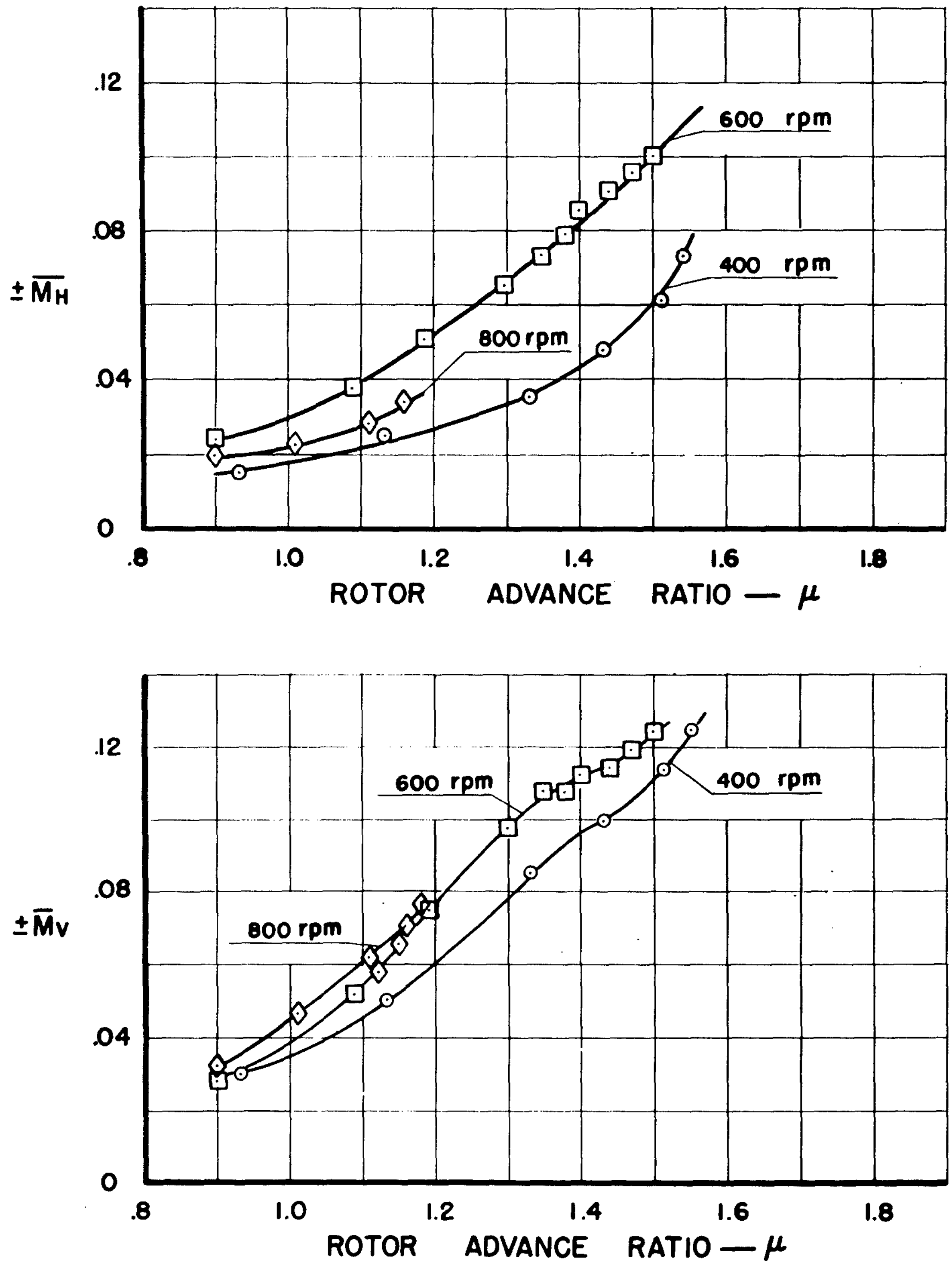

Figure 8: Variation of Rotor Blade Horizontal and Vertical Bending Moment Coefficients With Advance Ratio for Various Rotor Rotational Speeds, Configuration (a).

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

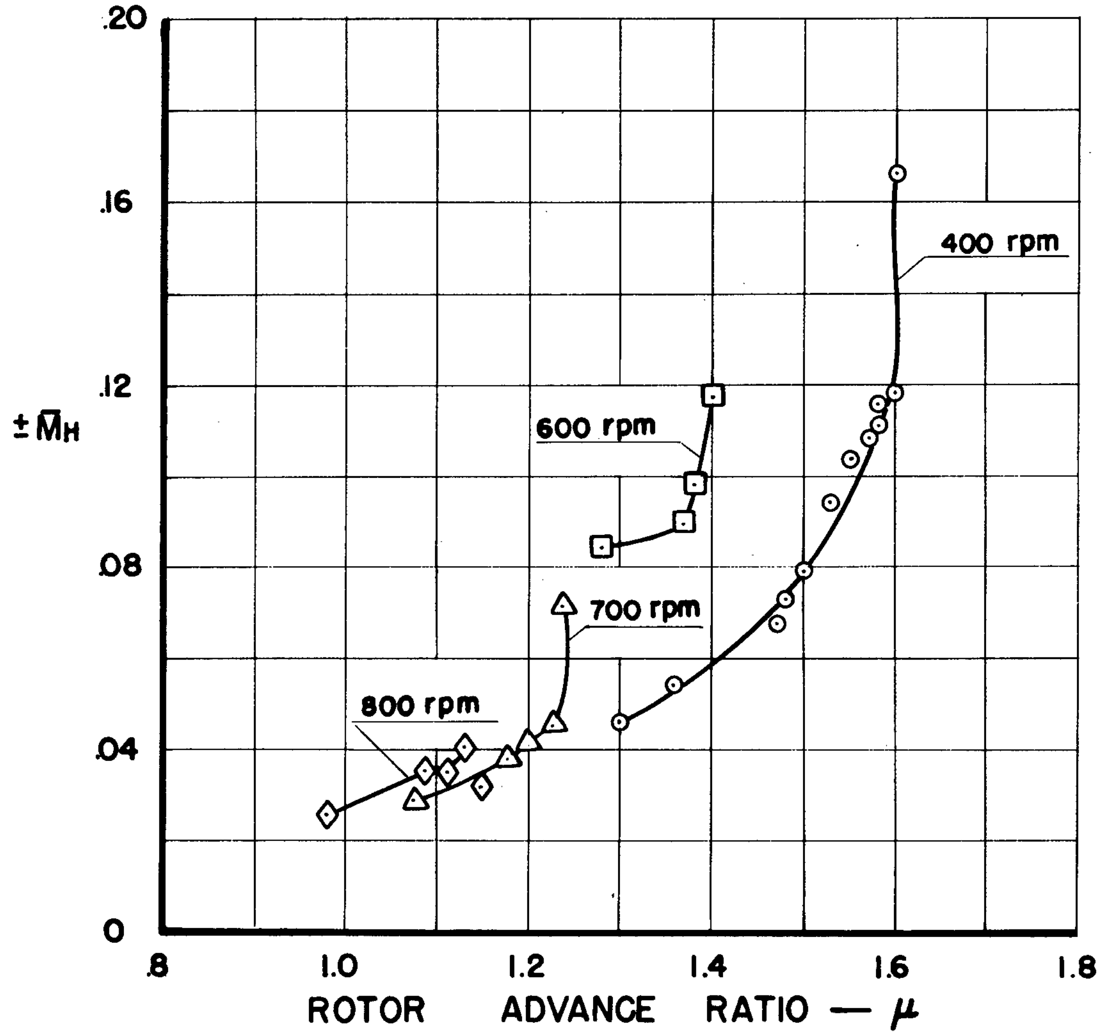

Figure 9: Variation of Rotor Blade Horizontal Bending Moment Coefficient With Advance Ratio for Various Rotor Rotational Speeds, Configuration (b).

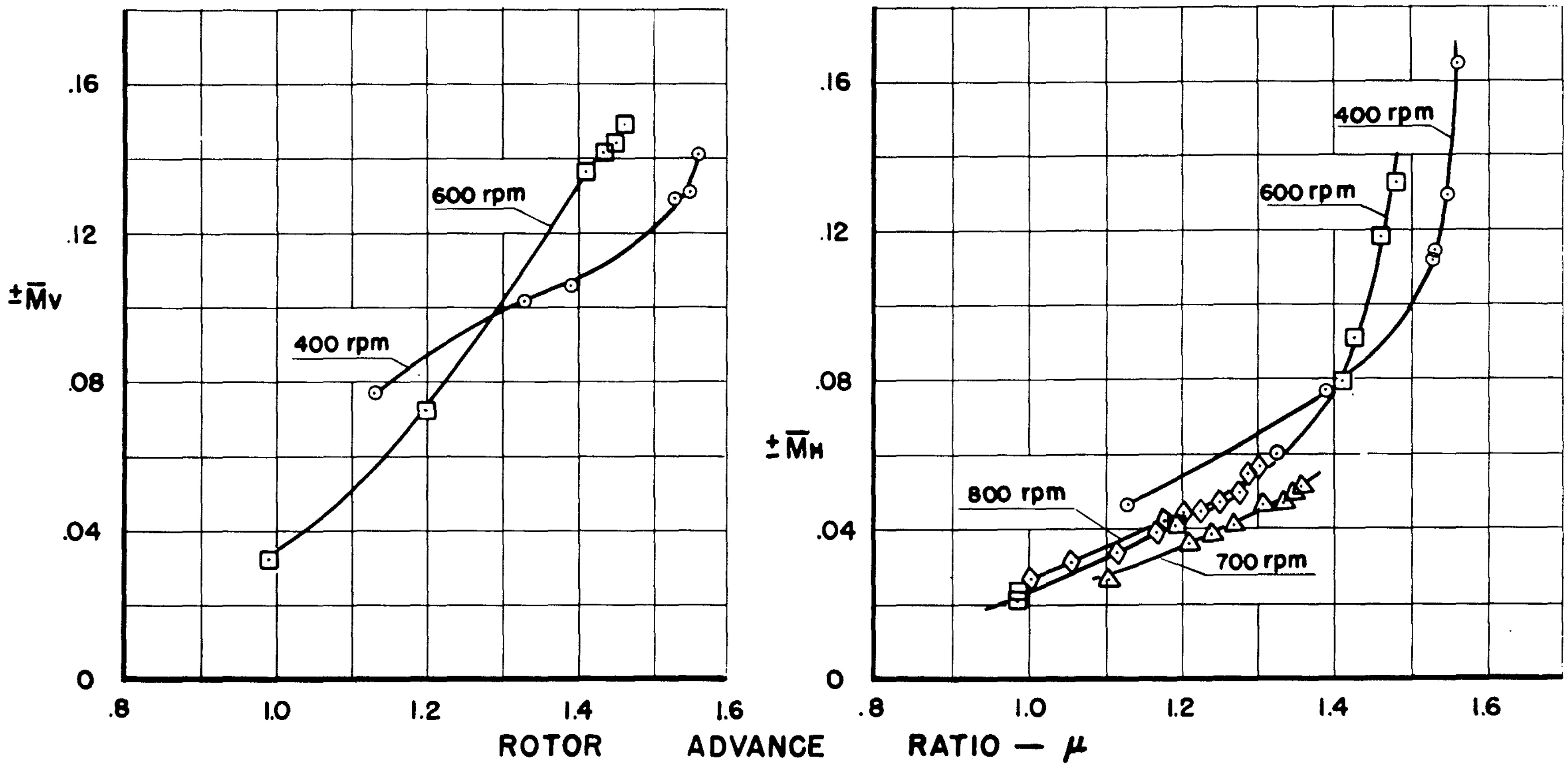

Figure 10: Variation of Rotor Blade Horizontal and Vertical Bending Moment Coefficients With Advance Ratio for Various Rotor Rotational Speeds, Configuration (c).

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MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

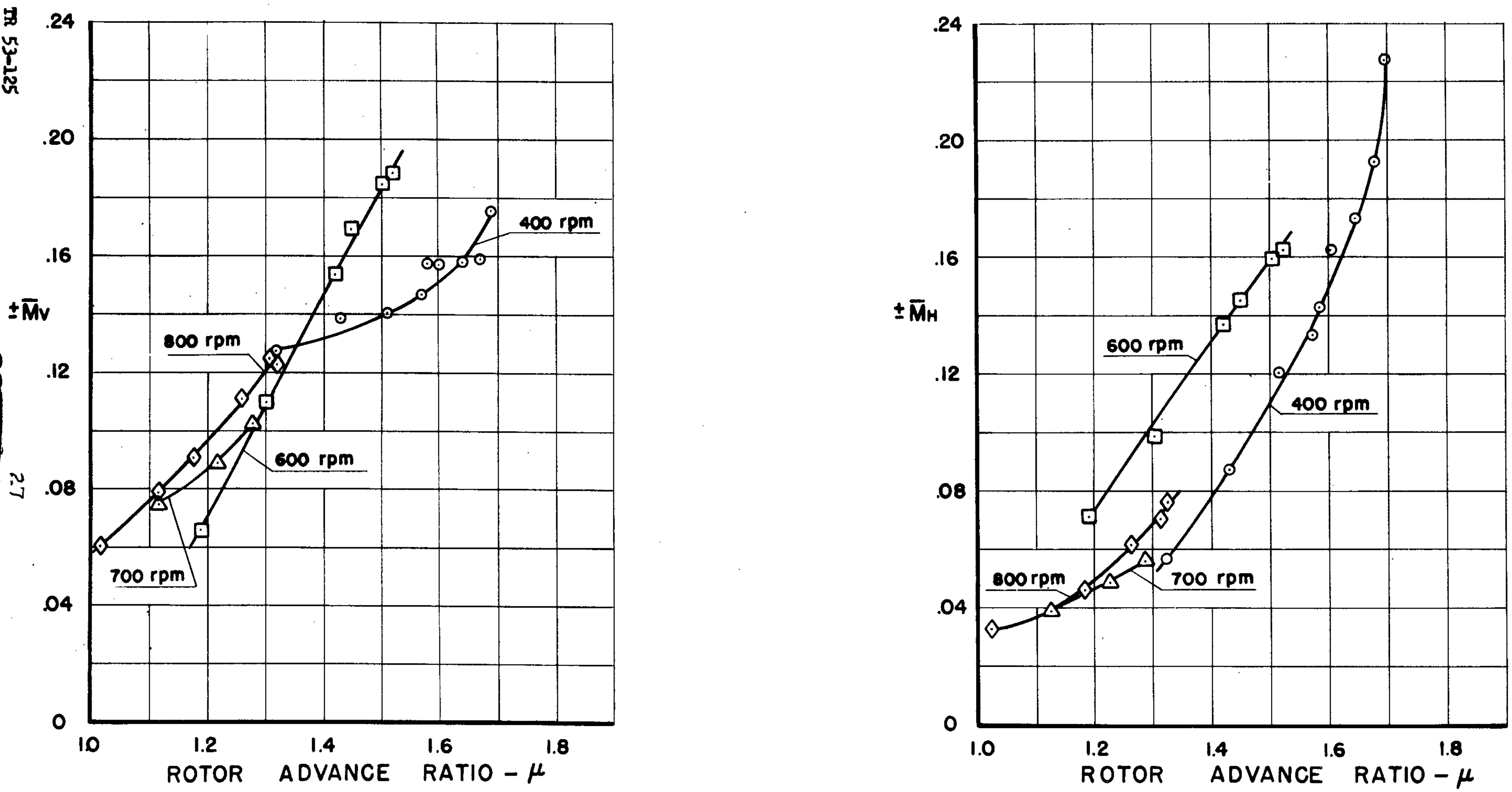

Figure 11: Variation of Rotor Blade Horizontal and Vertical Bending Moment Coefficients With Advance Ratio for Various Rotor Rotational Speeds, Configuration (d).

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MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

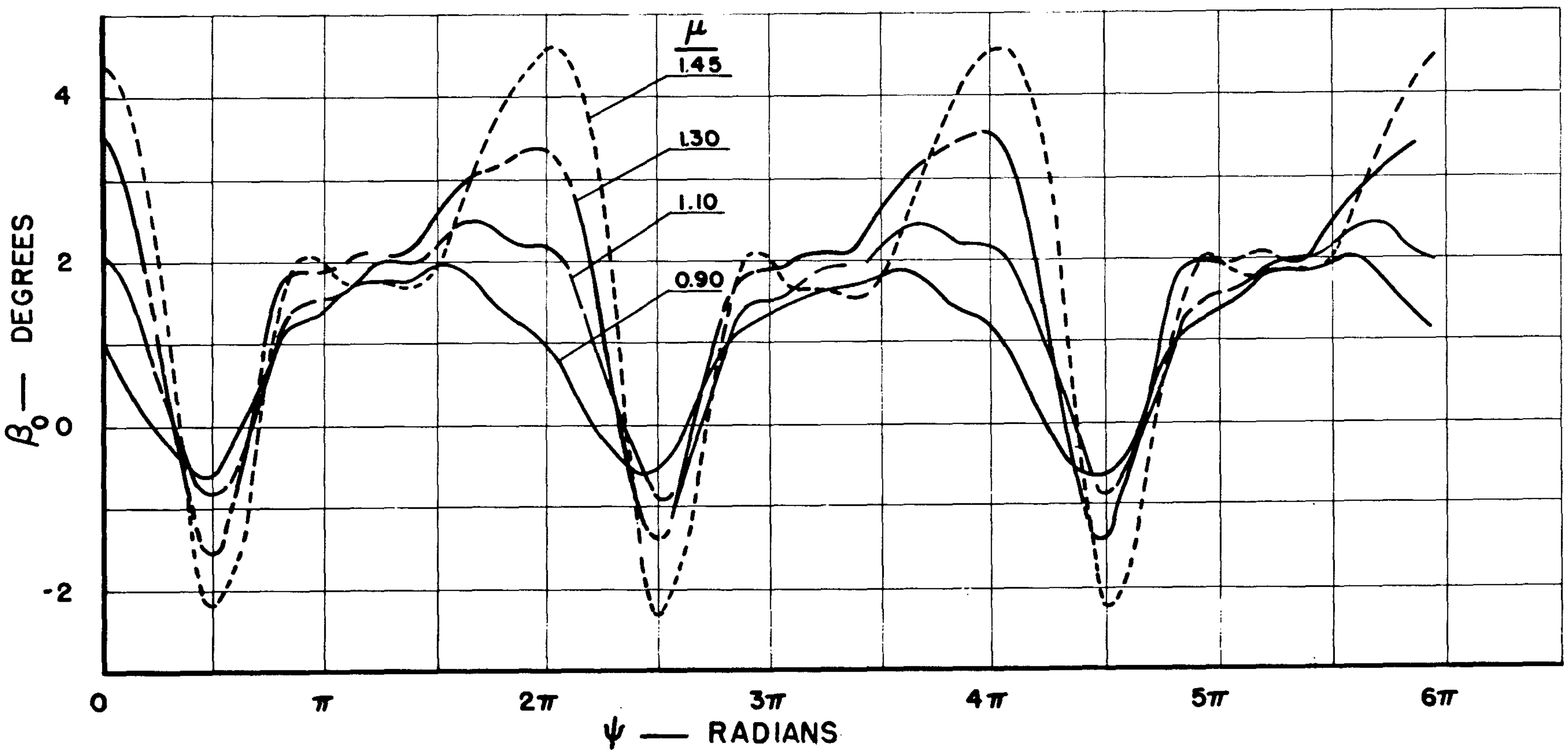
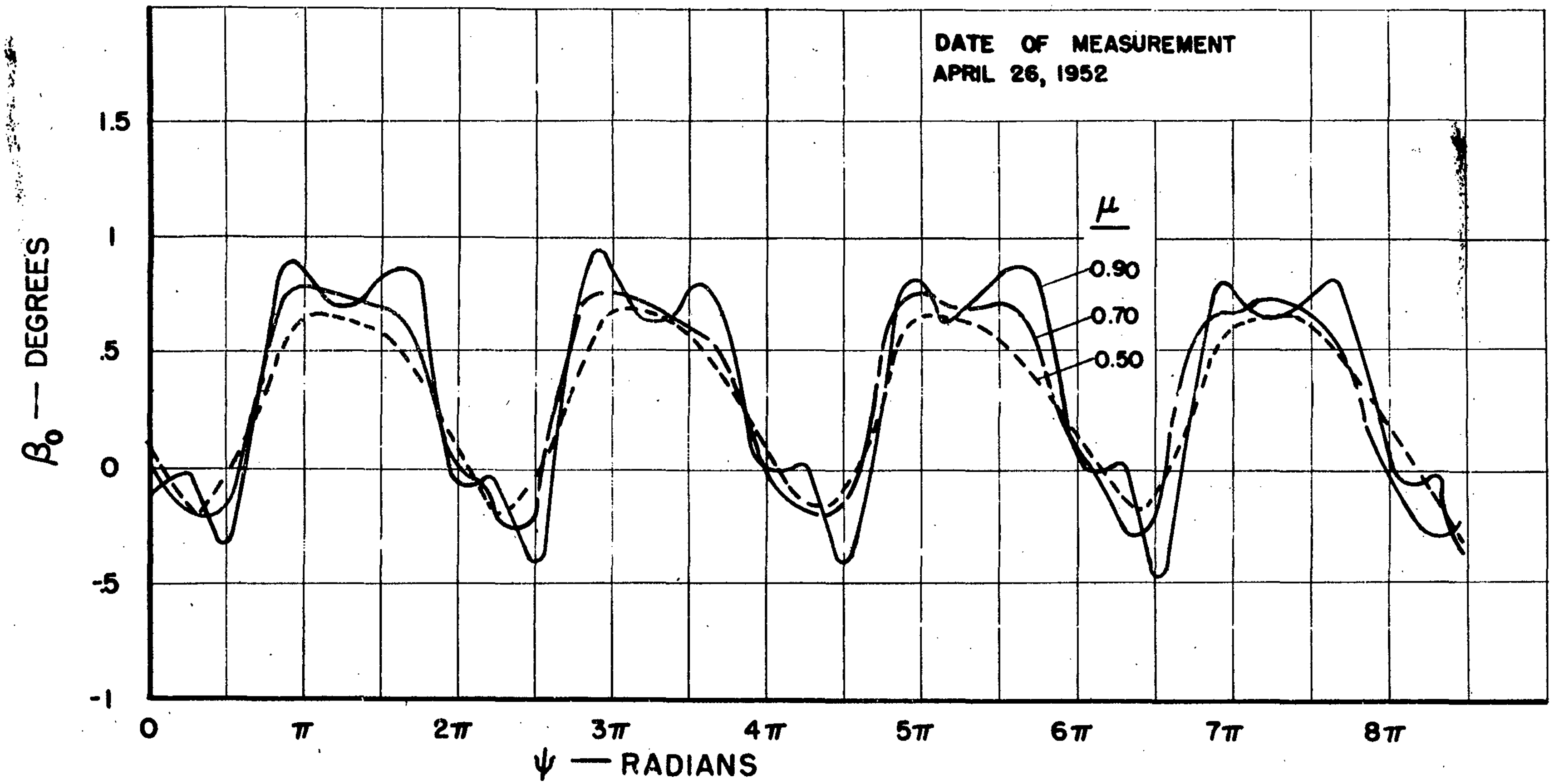
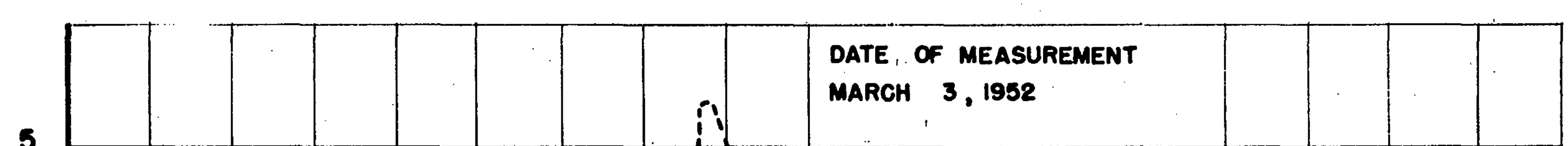


Figure 12: Variation of Rotor Blade Flapping Angle With Blade Azimuth Position for Several Advance Ratios at 400 rpm, Configuration (a).

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604





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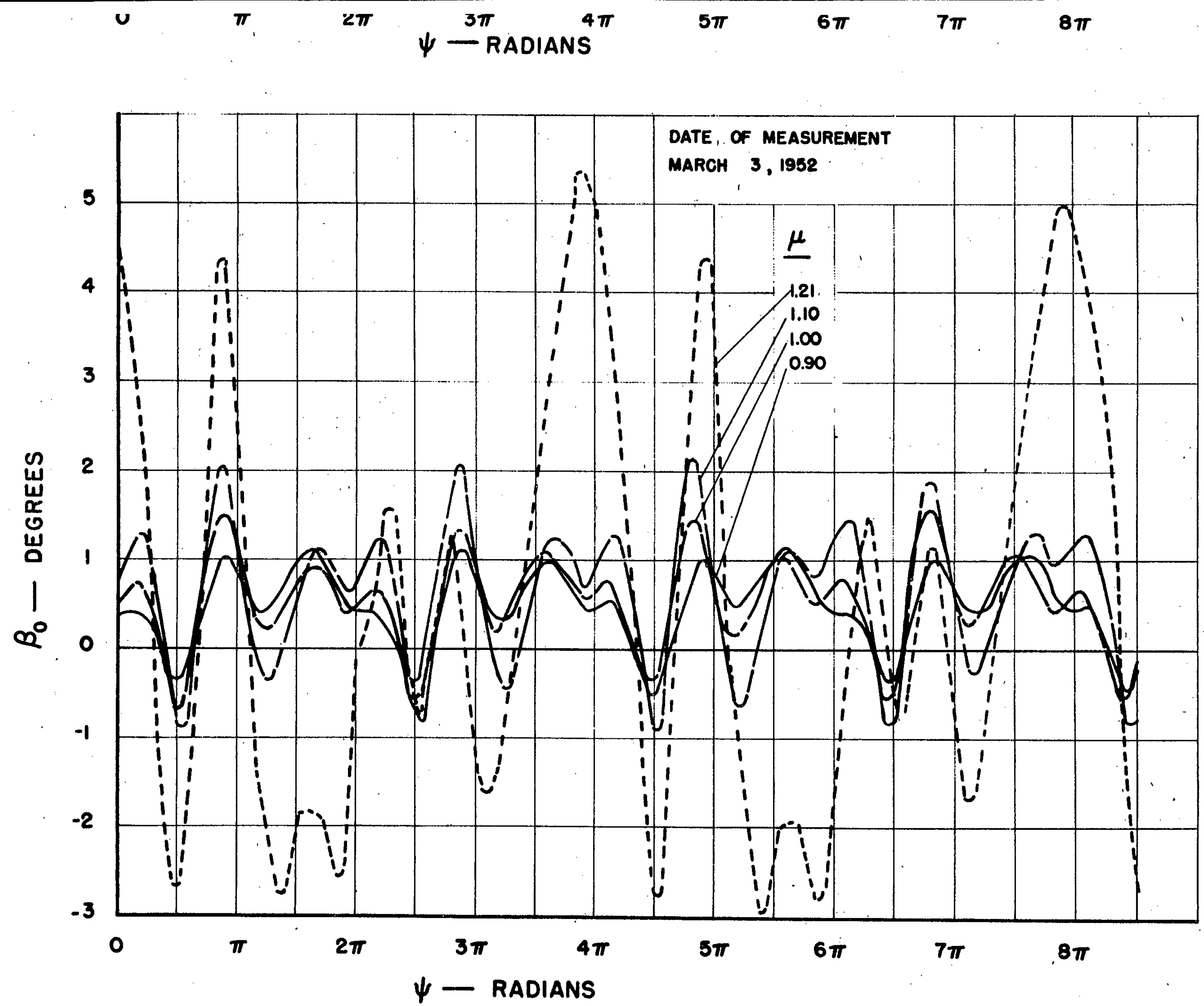

Figure 13: Variation of Rotor Blade Flapping Angle With Blade Azimuth Position for Several Advance Ratios at 800 rpm, Configuration (a).

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MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

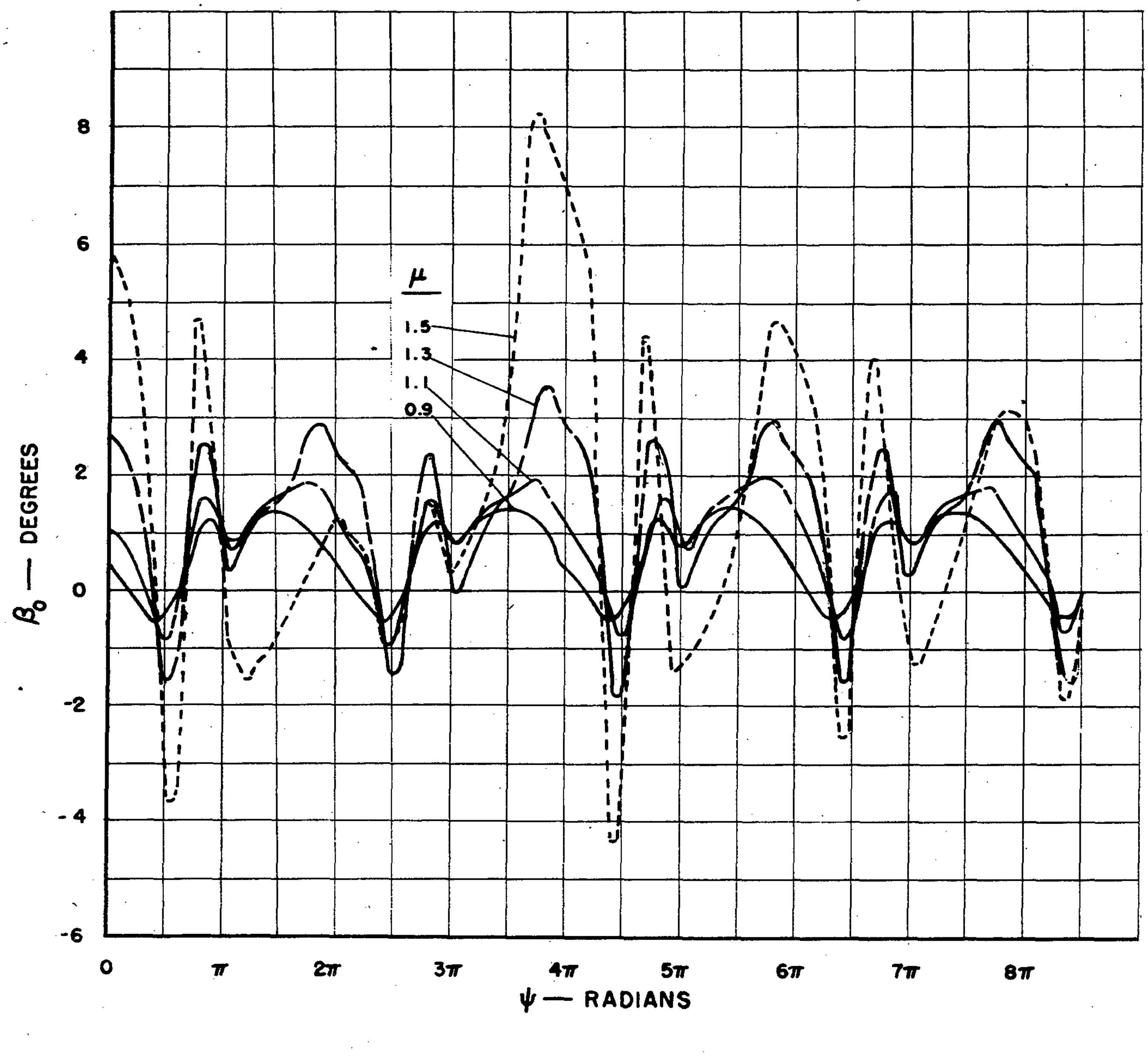

Figure 14: Variation of Rotor Blade Flapping Angle With Blade Azimuth Position for Several Advance Ratios at 600 rpm, Configuration (a).

MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

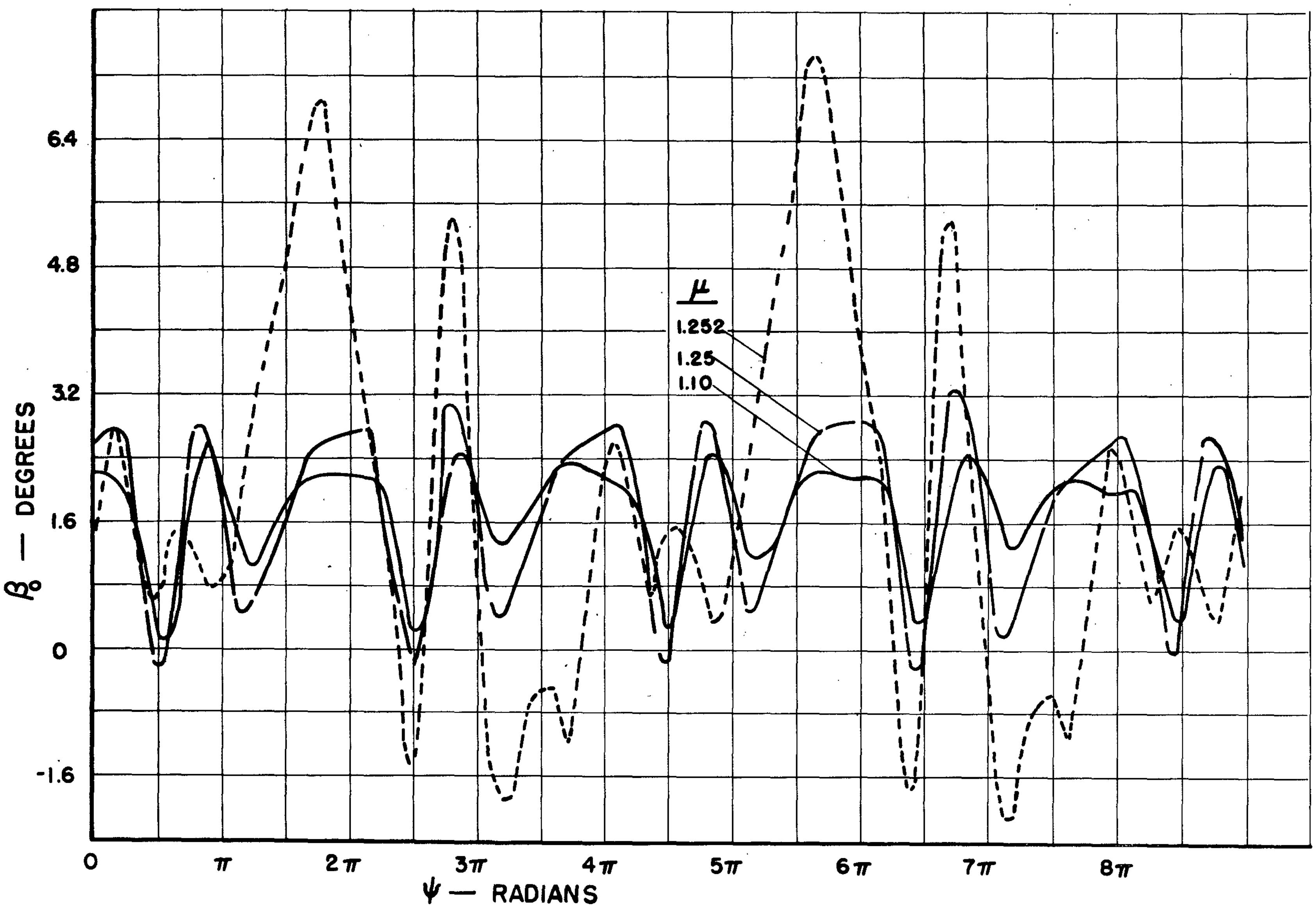

Figure 15: Variation of Rotor Blade Flapping Angle With Blade Azimuth Position for Several Advance Ratios at 700 rpm, Configuration (b).

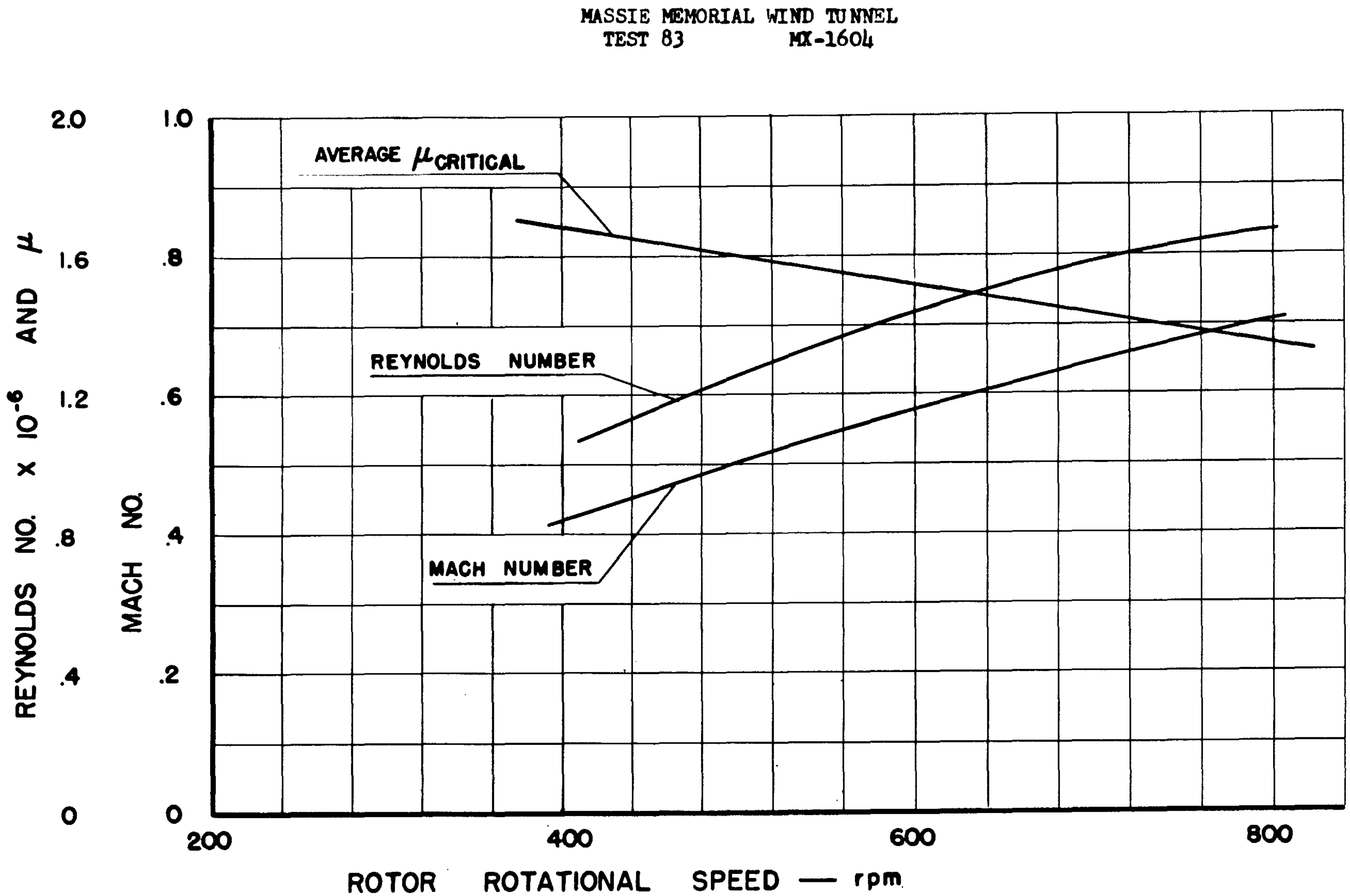

Figure 16: Variation of Rotor Blade Tip Reynolds Number and Mach Number of the Advancing Blade at the Average Critical Advance Ratio and Average Critical Advance Ratio With Rotor Rotational Speed.

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MASSIE MEMORIAL WIND TUNNEL
TEST 83 MX-1604

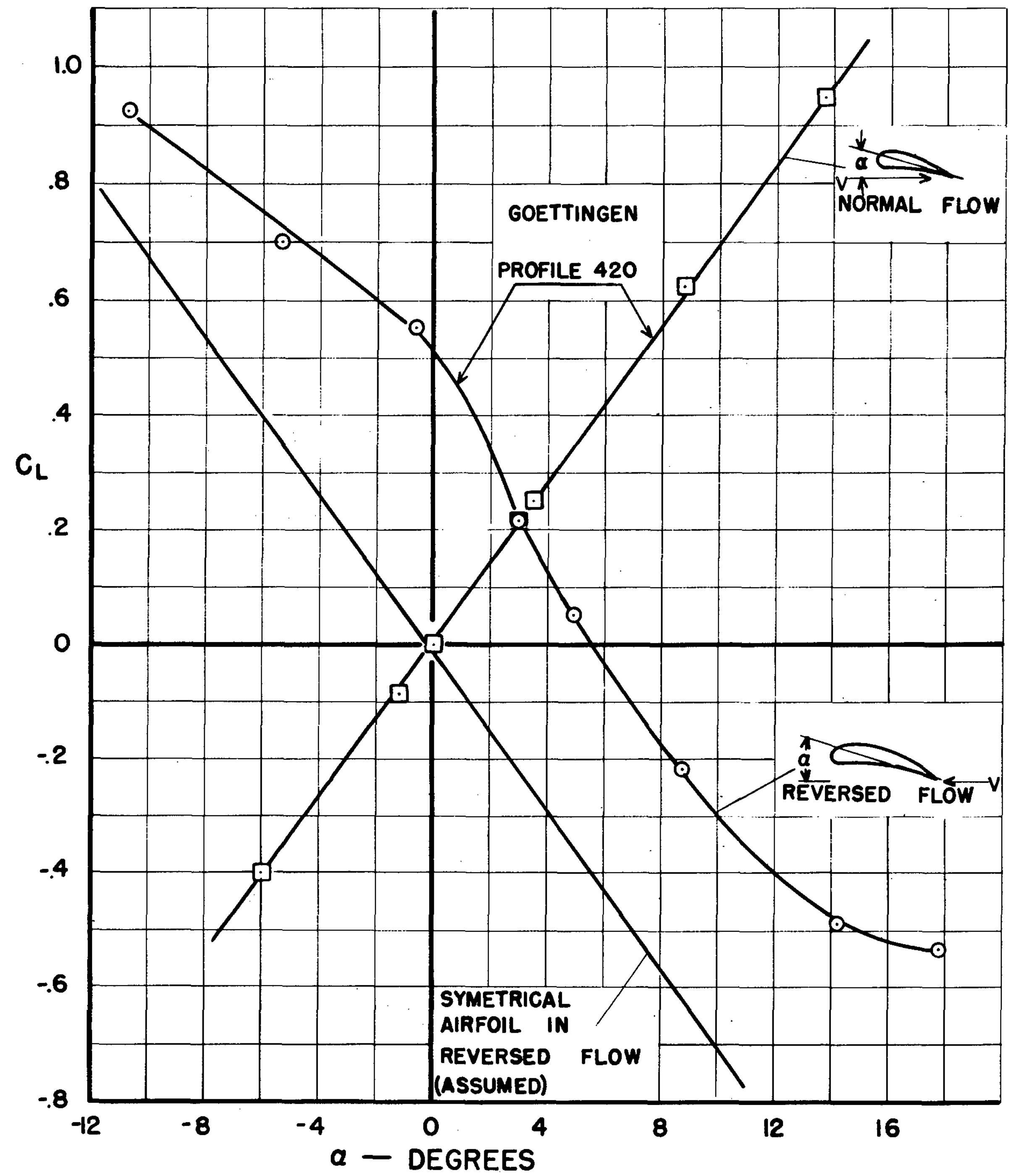

Figure 17a: Variation of Lift Coefficient With Angle of Attack for a Goettingen 420 Airfoil of Aspect Ratio 5 in Normal and Reversed Flow.

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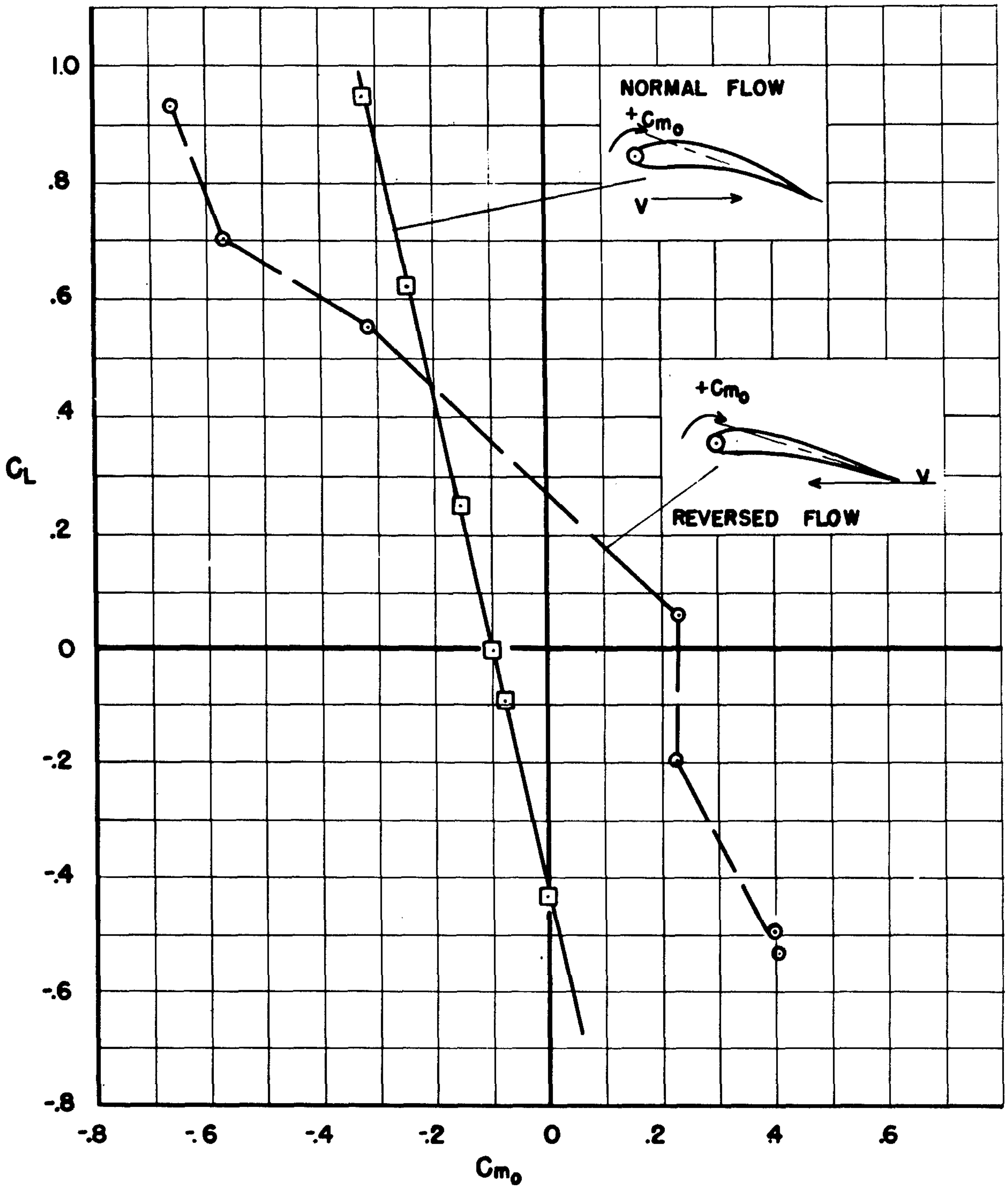

Figure 17b: Variation of Lift Coefficient With Moment Coefficient for a Goettingen 420 Airfoil of Aspect Ratio 5 in Normal and Reversed Flow.